



PERGAMON

Renewable and Sustainable Energy Reviews  
2 (1998) 3–24

---

---

**RENEWABLE  
& SUSTAINABLE  
ENERGY REVIEWS**

---

---

# Chapter 1—Thermal comfort and the development of bioclimatic concept in building design

Ali Sayigh<sup>a,\*</sup>, A. Hamid Marafia<sup>b</sup>

<sup>a</sup>*University of Hertfordshire, Reading, U.K.*

<sup>b</sup>*College of Engineering, University of Qatar, Doha, Qatar*

## 1. Introduction

In the past few decades, there have been several attempts to develop a systematic methodology for adapting the design of a building to human requirements and climatic conditions. Such attempts include the development of the building bioclimatic charts and Mahony tables. These attempts were aimed at defining the appropriate building design strategies, for a certain region. This chapter details an attempt to adopt the building bioclimatic chart concept as well as Mahony tables to Qatar, which is used as an example, in order to determine the most appropriate building design strategies.

## 2. Thermal comfort

According to ASHRAE 55-74 standard [1], thermal comfort is defined as “That condition of mind which expresses satisfaction with the thermal environment”. However, the comfort zone is defined as the range of climatic conditions within which the majority of people would not feel thermal discomfort, either of heat or cold. Thermal comfort studies either based on field surveys or on controlled climatic chambers. The Fanger comfort equation and Humphrey’s Thermal Neutrality correlation are among the most commonly adopted concepts.

---

\* Corresponding author. Tel: 0044 01189 611364; Fax 0044 01189 611365; E-mail: asayigh@net-com.co.uk

### 2.1. Fanger thermal equation

Macpherson [2] identified six factors that affect thermal sensation. These factors are air temperature, humidity, air speed, mean radiant temperature (MRT), metabolic rate and clothing levels. He also identified nineteen indices for the assessment of the thermal environment. Each of these indices incorporate one or more of the six factors.

The Fanger comfort equation is the most commonly adopted. It is based on experiments with American college-age persons exposed to a uniform environment under steady state conditions. The comfort equation establishes the relationship among the environment variables, clothing type and activity levels. It represents the heat balance of the human body in terms of the net heat exchange arising from the effects of the six factors identified by Macpherson. The satisfaction of eqn (1) is a necessary condition for optimal comfort.

$$\begin{aligned} (M/A_{Du})(1-\eta) - 0.35[1.92t_s - 25.3 - P_a] - (E_{sw}/A_{Du}) - 0.0023(M/A_{Du})(44 - P_a) \\ - 0.0014(M/A_{Du})(34 - t_a) = 3.4 \times 10^{-8} f_{cl}[t_{cl} + 273]^4 - (t_{mrt} + 273)^4 \\ + f_{cl}h_c(t_{cl} - t_a) \end{aligned} \quad (1)$$

Equation (1) contains three physiological variables; the heat loss by evaporation of sweat, skin temperature and metabolic rate. Based on his experimental data and others, Fanger proposed the following equations for these variables as functions of the internal heat production per surface area,  $(H/A_{Du})$

$$t_s = 35.7 - 0.032(H/A_{Du}) \quad (2)$$

$$E_{sw} = 0.42 A_{Du}[(H/A_{Du}) - 50] \quad (3)$$

Substituting eqns (2) and (3) into eqn (1) Fanger derived the general comfort equation

$$\begin{aligned} (M/A_{Du})(1-\eta) - 0.35[43 - 0.061(M/A_{Du})(1-\eta) - P_a] \\ - 0.42[(M/A_{Du})(1-\eta) - 50] - 0.0023(M/A_{Du})(44 - P_a) - 0.0014(M/A_{Du})(34 - t_a) \\ = 3.4 \times 10^{-8} f_{cl}[t_{cl} + 273]^4 - (t_{mrt} + 273)^4 + f_{cl}h_c(t_{cl} - t_a) \end{aligned} \quad (4)$$

It is clear from eqn (4) that the human thermal comfort is a function of:

- (i) The type of clothing  $t_{cl}, f_{cl}$
- (ii) The type of activity,  $\eta, V$  and  $M/a_{Du}$
- (iii) Environmental variables  $V, t_a, t_{mrt}$  and  $P_a$

### 2.2. Predicted mean vote (PMV)

The thermal comfort equation is only applicable to a person in thermal equilibrium with the environment. However, the equation only gives information on how to reach optimal thermal comfort by combining the variables involved. Therefore, it is not

directly suitable to ascertain the thermal sensation of a person in an arbitrary climate where these variables may not satisfy the equation. Fanger used the heat balance equation to predict a value for the degree of sensation using his own experimental data and other published data for any combination of activity level, clothing value and the four thermal environmental parameters. As a measure for the thermal sensation index the commonly used seven point psycho-physical ASHRAE scale was employed. Table 1 summarises the commonly used scales. The term Predicted Mean Vote (PMV) is the mean vote expected to arise from averaging the thermal sensation vote of a large group of people in a given environment. The PMV is a complex mathematical expression involving activity, clothing and the four environmental parameters. It is expressed by eqn (5)

$$\begin{aligned}
 PMV = & (0.352e^{-0.042(M/A_{Du})} + 0.032)[M/A_{Du}](1 - \eta) \\
 & - 0.35[43 - 0.061(M/A_{Du})(1 - \eta) - P_a] \\
 & - 0.42[M/A_{Du}](1 - \eta) - 50] - 0.0023(M/A_{Du})(44 - P_a) \\
 & - 0.0014(M/A_{Du})(34 - t_a) - 3.4 \times 10^{-8} f_{cl}[t_{cl} + 273]^4 \\
 & - (t_{mrt} + 273)^4] + f_{cl}h_c(t_{cl} - t_a)
 \end{aligned} \tag{5}$$

here  $h_c$  is calculated as follows:

$$\begin{aligned}
 h_c &= 2.05(t_{cl} - t_a)^{0.25} \text{ for } 2.05(t_{cl} - t_a)^{0.25} > 10.4\sqrt{V} \\
 h_c &= \sqrt{V} \text{ for } 2.05(t_{cl} - t_a)^{0.25} < 10.4\sqrt{V}
 \end{aligned}$$

The thermal sensation scales assumes equal intervals between the expressions of thermal sensation. Hence, the degree of deviation from the neutral or optimal conditions of thermal comfort are transferred into numbers rather than expressions. Such transformation of the facts from expressions to numbers enabled the workers to further investigate the percentages of responses of individuals to certain conditions. The conditions vary according to environmental, human activity level and body insolation factors. Accordingly, such conditions can be plotted in thermal comfort charts. From these charts the level of thermal comfort can be measured at certain conditions of the previously mentioned factors. Fanger [3] suggested such charts

Table 1  
Thermal sensation scales

Expression	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
ASHRAE	1	2	3	4	5	6	7
Fanger	−3	−2	−1	0	1	2	3

which were updated and modified afterwards. Based on more recent research Markus and Morris [4] worked out 55 thermal comfort charts. The scale used is similar to Fanger's PMV, with neutrality at zero, with negative values in the cold and positive ones on the warm. The charts have two distinct advantages. First, they have been validated over a wide range of conditions and not merely the normal 'room' conditions. Second, they express judgements in degrees of discomfort (DISC) and thus equivalences can be found between cold and warm conditions in terms of a common human response. Between DISC  $-0.5$  and  $+0.5$ , 80% of the population will be satisfied, and between  $-1.0$  and  $+1.0$ , it drops to 70%. The charts were based on a range of human activities, environmental conditions and body insulation factors:

- (i) Clothing: 0.0 (nude), 0.6, 0.9, 2.4 and 4.0 clo.
- (ii) Activity: 1, 3 and 5 Met.
- (iii) Air velocity: 0.1, 0.5, 2.0, 5.0 and 10  $\text{ms}^{-1}$ .

Knowing the activities of the people inside a specific space, their type of clothing and air velocity inside the space, one can obtain from the thermal comfort charts the following design parameters:

- (i) The standard effective temperature, SET.
- (ii) The degree of discomfort, DISC;
- (iii) The skin wettedness,  $w$  (which is defined as the equivalent percentage of the human body which is covered with moisture).

The thermal comfort chart presented, as an example, in Fig. 1 for the conditions of 0.6 clo. of clothing, 0.1  $\text{ms}^{-1}$  air velocity (still air) and 1.0 Met of activity (sedentary).

### 2.3. Thermal neutrality

Humphrey [5] Auliciemes investigated the thermal neutrality of the human body. It was defined as the temperature at which the person feels thermally neutral (comfortable). Their studies were based on laboratory and field works in which people were thermally investigated under different conditions. The results of their experiments were statistically analysed by using regression analysis. Figure 2 shows that thermal neutrality as a function of the prevailing climatic conditions. Humphreys showed that 95% of the neutral temperature is associated with the variation of outdoor mean temperature. For free running buildings, the regression equation is approximated by

$$T_n = 11.9 + 0.534T_m \quad (6)$$

A different empirical correlation function was carried out by Auliciemes is

$$T_n = 17.6 + 0.314T_m \quad (7)$$

Based on the above equations, the predicted neutral temperature for Qatar for the different months of the year are as indicated in Table 2. Table 2 indicates that Auliciemes overvalues the thermal neutrality temperatures for the winter months,

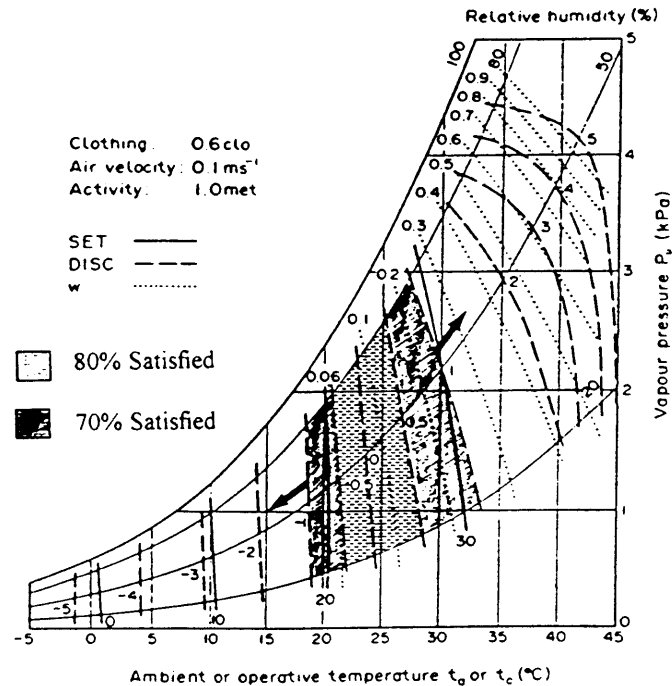


Fig. 1. The thermal comfort chart, for the conditions: 0.6 clo,  $0.1 \text{ ms}^{-1}$  and 1.0 Met [4].

while Humphrey does the same for the summer months. The summer neutrality temperature for Qatar is about  $28.5^\circ\text{C}$  whereas in winter it drops to about  $23^\circ\text{C}$ .

### 3. Degree day method for estimating heating and cooling requirements for Qatar

The degree day method is a pure climatic concept to estimate the cooling and heating requirements at any location. It can be visualized as the annual cumulative time weighted temperature deficit (heating degree-days) or surplus (cooling degree-days). A reference temperature is set and every days mean outdoor temperature is compared with the reference temperature. The differences are added for every day to give the annual number of degree days. Table 3 lists the annual cooling and heating degree days for Qatar. Two reference temperatures were considered, according to ASHRAE standard and Humphreys neutral temperature as indicated in Table 3. The reference temperatures for Qatar, in accordance with ASHRAE standard, are generally lower than that estimated by Humphrey's equation. This resulted in higher cooling degree days and lower heating degree days with ASHRAE standard compared to those obtained with Humphreys correlation. It is also clear from Table 3 that the

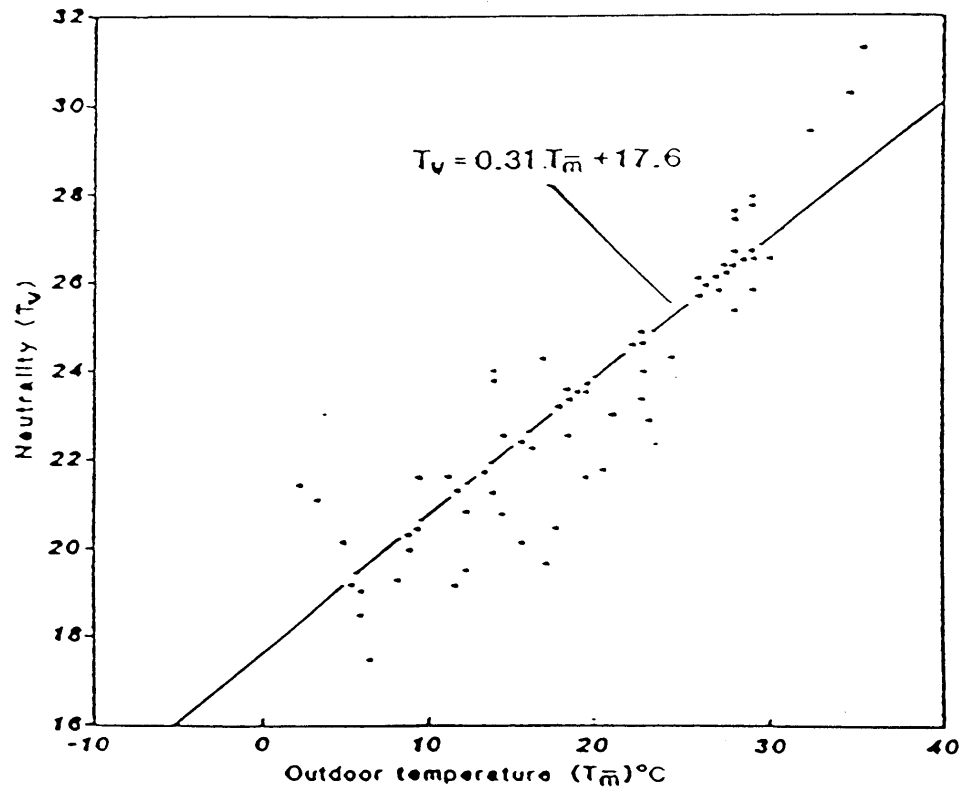


Fig. 2. Correlation of outdoor mean temperature and thermal neutrality [5].

Table 2

Thermal neutrality temperatures for Qatar

Month	Humphreys $T_n(^{\circ}\text{C})$	Auliciemes $T_n(^{\circ}\text{C})$
J	20.9	22.7
F	22.0	23.2
M	23.5	24.2
A	26.0	25.7
M	29.2	27.5
J	30.1	28.0
J	31.0	28.5
A	30.9	28.5
S	29.8	27.8
O	27.7	26.6
N	25.5	25.4
D	20.8	22.7

Table 3  
Degree day method applied to Qatar based on ASHRAE standard and neutrality temperature concept

Month	Cooling Degree-Days $T_{\text{ref}} = 26^{\circ}\text{C}$		Heating Degree-Days $T_{\text{ref}} = 18.3^{\circ}\text{C}$	
	ASHRAE $T_{\text{ref}} = 26^{\circ}\text{C}$	Humphrey's $T_n = 28.5$	ASHRAE $T_{\text{ref}} = 18.3^{\circ}\text{C}$	Humphrey's $T_n = 23^{\circ}\text{C}$
J	0	0	59	202
F	0	0	73	195
M	0	0	2	49
A	31	7	0	0
M	180	102	0	0
J	227	152	0	0
J	286	208	0	0
A	280	203	0	0
S	209	134	0	0
O	90	25	0	0
N	6	0	0	0
D	0	0	68	133
Total	1309	831	202	578

cooling requirements are high, and generally, extending from May to October. The months of March, April and November can be considered as being comfortable.

#### 4. Building bioclimatic charts

Bioclimatic charts facilitate the analysis of the climate characteristics of a given location from the viewpoint of human comfort, as they present, on a psychrometric chart, the concurrent combination of temperature and humidity at any given time. They can also specify building design guidelines to maximize indoor comfort conditions when the building's interior is not mechanically conditioned. All such charts are structured around, and refer to, the 'comfort zone'. The comfort zone is defined as the range of climatic conditions within which the majority of persons would feel thermally comfortable.

##### 4.1. Olgyays bioclimatic chart

Olgyays bioclimatic chart [6], Fig. 3, was one of the first attempts at an environmentally conscious building design. It was developed in the 1950s to incorporate the outdoor climate into building design. The chart indicates the zones of human comfort in relation to ambient temperature and humidity, mean radiant temperature (MRT), wind speed, solar radiation and evaporative cooling. On the chart, dry bulb tem-

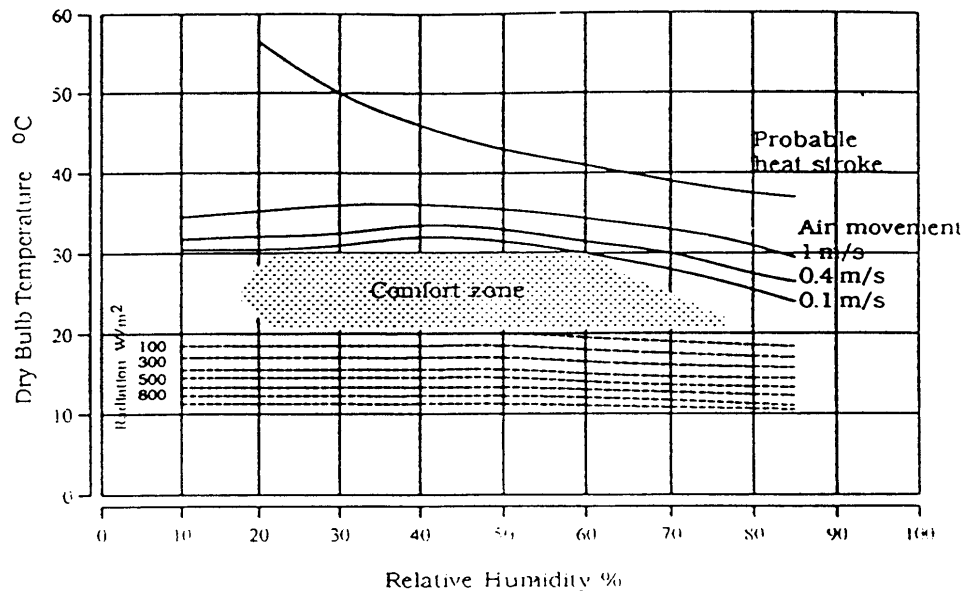


Fig. 3. Olgyays building bioclimatic chart [6].

perature is the ordinate and relative humidity is the abscissa. The comfort zone is in the centre, with winter and summer ranges indicated separately (taking seasonal adaptation into account). The lower boundary of the zone is also the limit above which shading is necessary. At temperatures above the comfort limit the wind speed required to restore comfort is shown in relation to humidity. Where the ambient conditions are hot and dry, the evaporative cooling (EC) necessary for comfort is indicated. Variation in the position of the comfort zone with mean radiant temperature (MRT) is also indicated.

#### 4.1.1. Limitations and problems impairing the use of Olgyays bioclimatic chart

The concept of the chart was based on the outdoor climatic conditions. This resulted in some limitations in analysing the physiological requirements of the indoor environment of the building. Therefore the chart is applicable to a hot humid climate since there is no high range fluctuations between indoor and outdoor conditions.

#### 4.1.2. Applicability of Olgyays bioclimatic chart to Qatar

The bioclimatic chart of Qatar is shown in Fig. 4. The twelve lines represent the different months of the year. They represent the average daily maxima and average daily minima data of both relative humidity and dry bulb temperature. The chart indicates that for the months of April–June, October and November shading ventilation can be effective tools in restoring comfort. On the other hand, for the months of July, August and September the temperature and relative humidity is so high that only conventional dehumidification and air conditioning can restore comfort. For the



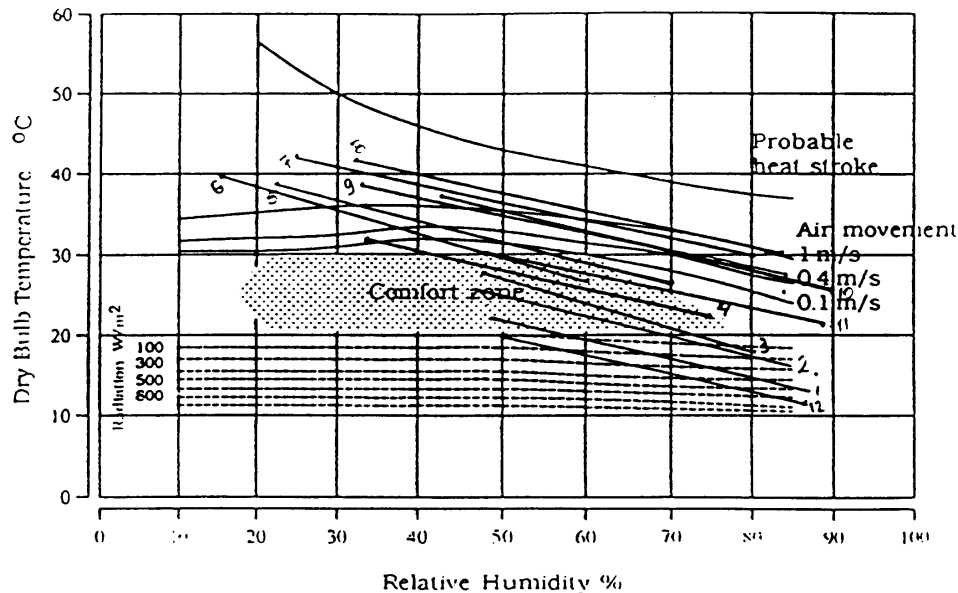


Fig. 4. Olgyays chart applied to Qatar.

winter months (December–March) the chart indicates that solar radiation should be encouraged. For example, in January, the radiation needed to bring the outdoor condition to the lower limit of the comfort zone is about  $600 \text{ Wm}^{-2}$ .

#### 4.2. Givoni's bioclimatic chart

Givoni's bioclimatic chart [7], Fig. 5, aimed at predicting the indoor conditions of the building according to the outdoor prevailing conditions. He based his study on the linear relationship between the temperature amplitude and vapour pressure of the outdoor air in various regions. In his chart and according to the relationship between the average monthly vapour pressure and temperature amplitude of the outdoor air, the proper passive cooling strategies are defined according to the climatic conditions prevailing outside the building envelope. The chart combines different temperature amplitude and vapour pressure of the ambient air plotted on the psychrometric chart and correlated with specific boundaries of the passive cooling techniques overlaid on the chart. These techniques include evaporative cooling, thermal mass, natural ventilation cooling, passive heating.

##### 4.2.1. Limitations of Givoni's bioclimatic chart

In 1981 Watson [8] identified the limitations of Givoni's bioclimatic chart analysis as:

- (i) It can be applied mainly to residential scale structures which are free of any internal heat gains.

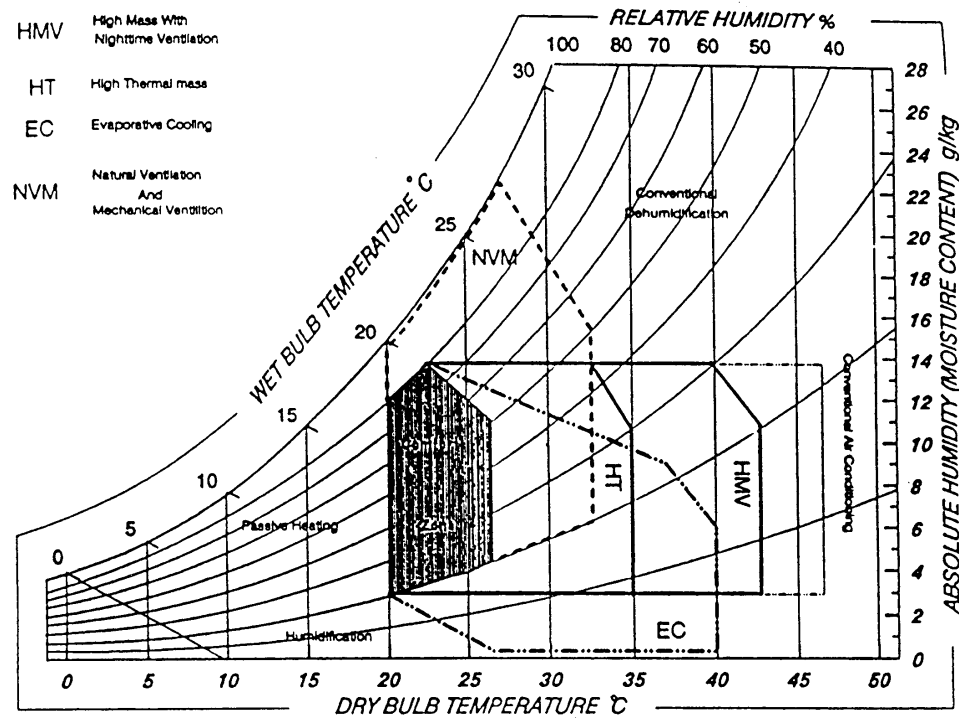


Fig. 5. Givoni's building bioclimatic chart [6].

- (ii) The ventilation upper boundary zone is based on the assumption that indoor mean radiant temperature and vapour pressure are nearly the same as those of the external environment. This necessitates a building of low mass and an exterior structure of medium to high thermal resistance provided with white external paint.
- (iii) The thermal mass effectiveness is based on the assumption that all windows are closed during the daytime, a still indoor air and the indoor vapour pressure is 2 mm higher than the outside.

#### 4.2.2. Applicability of Givoni's bioclimatic chart to Qatar

The chart applied to Qatar is shown in Fig. 6. The chart indicates that high mass building coupled with night time ventilation can effectively restore comfort for the months of April, May, June, October and November. However, for the months of July, August and September, the high ambient temperature and humidity indicate that passive techniques are ineffective and conventional means (dehumidification and air conditioning) are therefore essential to restore comfort in buildings. Furthermore, passive heating can restore comfort from December through March.

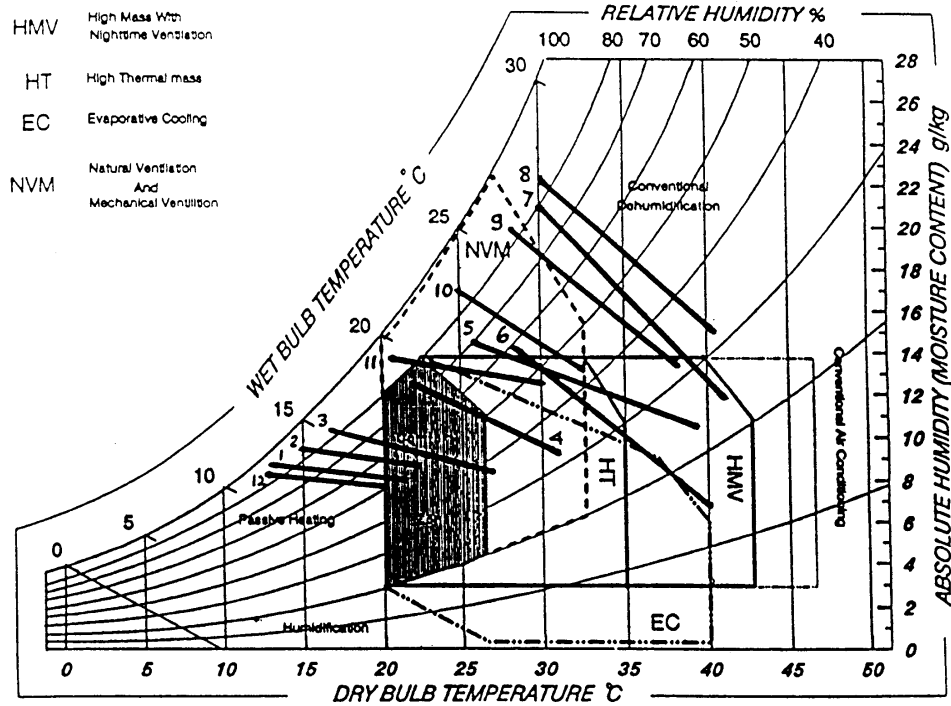


Fig. 6. Givoni's building bioclimatic chart applied to Qatar.

#### 4.3. Szokolay's bioclimatic chart

Givoni, in 1970, published his analysis of the Index of Thermal Stress, which was followed by Humphreys [5] in 1978 and Auliciemes in 1982 with their Thermal Neutrality equations. Szokolay [9] in 1986 brought these separate strands of thought together and developed the concept that, depending on the location and the people of that location, there are, in fact, two comfort zones rather than one, Fig. 7. The zones are based on thermal neutrality correlated to the outdoor mean temperature ( $T_m$ ) by eqn (8):

$$T_n = 17.6 + 0.31T_m \quad (8)$$

Equation (8) is only valid under the following conditions:

- (i)  $18.5 < T_n < 28.5$
- (ii) The width of the comfort zone is 2 K at 50% relative humidity.
- (iii) Humidity boundaries are based on ASHRAE standard 55-81 which set the lower and upper limits at 4–12 g kg<sup>-1</sup> moisture content (AH).
- (iv) Relative humidity should not exceed 90% RH curve.

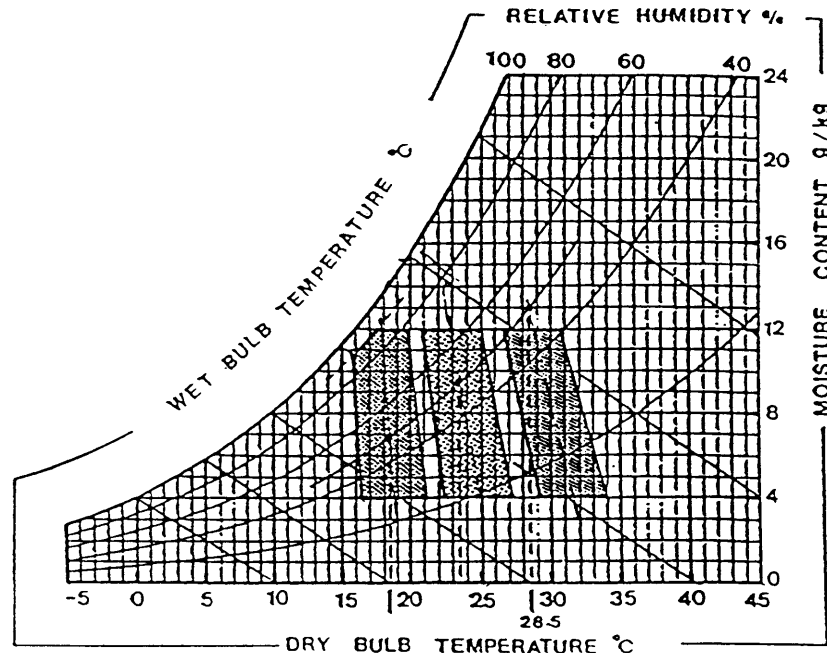


Fig. 7. Szokolay control potential zone chart [9].

#### 4.3.1. Applicability of the control potential zones (CPZ) to Qatar

The control potential zones indicate that the strategies which can be followed to restore comfort in buildings in Qatar are similar to those indicated by Givoni's bioclimatic chart, Fig. 8.

### 5. Problems impairing the use of the bioclimatic charts

Arens [10] discussed the problems impairing the use of the bioclimatic charts. Such problems include:

- (i) The monthly average of wind, humidity and temperature are a poor representation of the widely varying coincident occurrences of these variables.
- (ii) The result of the graphic method is not a measurable quantity: during some months it will be seen that ventilation is inadequate to provide comfort, but the number of hours in which this occurs during these months cannot be determined.
- (iii) There is no provision for cloth changing and activity levels throughout the day or seasons.
- (iv) The charts do not account for acclimatization. The effect of acclimatization and comfort expectations should be taken into account especially when comfort

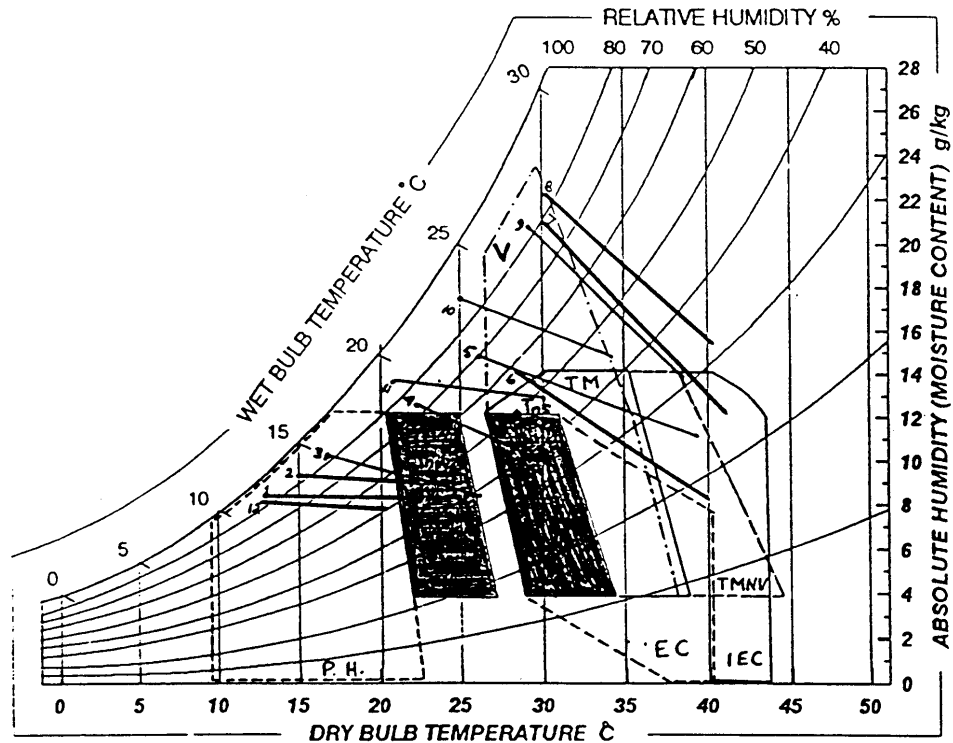


Fig. 8. Szokolay control potential zone applied to Qatar.

diagrams, and buildings design guidelines, are constructed for, and applied in, warm/hot developing countries [11].

## 6. Mahony tables

The Department of Development and Tropical Studies of the Architectural Association in London developed a methodology for building design in accordance to climate. The proposed methodology is based on three stages of design, the sketch design stage, the plan development stage and the element design stage. For the purpose of systematic analysis during the three stages, they introduced the Mahony Tables. The tables are used to analyse the climate characteristics, from which design indicators are obtained. From these indicators a preliminary picture of the layout, orientation, shape and structure of the climatic responsive design can be obtained. These tables are briefly described below.

### 6.1. Climatic data

The climatic data such as dry bulb temperature, relative humidity, precipitation and wind are classified into groups as described in Table 4.

Table 4  
Climatic data

Mean relative humidity	Humidity group
Below 30%	1
30–50%	2
50–70%	3
Above 70%	4

Similarly the monthly mean maxima and minima of the site in question are compared to the day and night comfort limits for each individual month, according to the annual mean ranges given in Table 8 respectively (i.e., maxima with the day comfort limit and minima with the night comfort limits). The classification is established as follows:

Above comfort limit    H  
 Within comfort limit    —  
 Below comfort limit    C

The humidity and comfort classifications are compared for each month to establish humidity and arid indicators.

#### 6.1.1. Humidity indicators

- H1 Indicates that air movement is essential. It applies when high temperature (day thermal stress = H) is combined with high humidity ( $HG = 4$ ) or when the high temperature (day thermal stress = H) is combined with moderate humidity ( $HG = 2$  or  $3$ ) and a small diurnal range ( $DR < 10$  C).
- H2 Indicates that air movement is desirable. It applies when temperature within the comfort limit (day thermal stress = —) are combined with high humidity ( $HG = 4$ )
- H3 Indicates that precautions against rain penetration are needed. Problems may arise with even low precipitation, but will be inevitable when rainfall exceeds 200 mm per month.

#### 6.1.2. Arid indicators

- A1 Need for thermal storage. This applies when a large diurnal range (10 C or more) coincides with moderate or low humidity ( $HG = 1, 2$  or  $3$ )
- A2 Indicates the desirability of outdoor sleeping space. It is needed when the night temperature is high (night thermal stress = H) and the humidity is low ( $HG = 1$  or  $2$ ). It may be needed also when nights are comfortable outdoors but hot indoors as a result of heavy thermal storage (day = H, night = —,  $HG = 1$  or  $2$  and when the diurnal range is above 10 C
- A3 Indicates winder or cold-season problem. These occur when day thermal stress = C.

Table 5  
Recommendations for building design in Qatar

Element	Recommendations
Layout	Building oriented on east-west axis to reduce exposure to sun Compact courtyard planning
Spacing	Open spacing for breeze penetration.
Air movement	Rooms single banked Permanent provision for air movement.
Openings	Size: medium openings, 20–40% Position: north and south walls at body height on windward side.
Walls and floors	Heavy external and internal walls.
Roofs	Light insulated roofs.
Outdoor sleeping	Space for outdoor sleeping is required.

Table 6  
Air temperature

Temperature (°C)	J	F	M	A	M	J	J	A	S	O	N	D
Monthly mean max.	21.0	22.1	26.3	31.3	38.6	39.7	41.3*	40.6	38.3	33.6	39.8	20.4
Monthly mean min.	12.4†	14.9	16.8	22.0	25.8	28.0	29.7	30.0	28.2	25.0	20.9	12.8
Monthly mean range	8.6	7.2	9.5	9.3	12.8	11.7	11.6	10.6	10.1	8.6	8.9	7.6

\* Highest monthly mean; † Lowest monthly mean; AMR = Annual mean range = Highest – Lowest = 28.9; AMT = Annual mean temperature = (Highest + Lowest)/2 = 26.9.

These tables are followed by the sketch design recommendations in which the design requirements of a building can be derived. The recommendations for the form of the building are grouped under the following eight subjects: Layout, space, air movement, openings, walls, roofs, outdoor space and rain protection.

At this stage, recommendations for the various size and protection of openings, layout planning, positioning, glazing, natural light and prevention of glare, along with the type of external walls, roofs and floors, could be indicated.

#### 6.1.2. Application of Mahoney's tables in Qatar

The climatic data of Qatar is Tabulated in Mahoney's Tables 6–11. The recommendations of the climatic analysis for building design are summarized in Table 5.

## 7. Conclusions

The following conclusions were arrived at:

- (1) The summer neutrality temperature for Qatar is about 28.5°C, whereas in winter

Table 7  
Comfort limits

		AMT over 20°C		AMT 15–20°C		AMT under 15°C	
Average R H HG		Day	Night	Day	Night	Day	Night
0–30	1	26–34	27–34	23–32	14–23	21–30	12 21
30–50	2	25–31	17–24	22–30	14–22	20–27	12 20
50–70	3	23–29	17–23	21–28	14–21	19–26	12 19
70–100	4	22–27	17–21	20–25	14–20	18–24	12 18

R H: relative humidity; HG: humidity group; AMT: annual mean temperature.

Table 8  
Humidity, rain and wind

R H (percentage)	J	F	M	A	M	J	J	A	S	O	N	D
Monthly mean max. a.m.	87.1	84.8	81.5	74.3	69.7	58.7	79.4	84	83.1	87.6	89	87.7
Monthly mean min. p.m.	49.5	52	38	32.7	24.1	17	25.5	33.3	33	43	48	51
Average	68.3	68.4	60	54	47	38	53	59	58	65	69	70
Humidity group	3	3	3	3	2	2	3	3	3	3	3	3
Rainfall (mm)	6.8	1.3	68.9	12.8	0	0	0	0	0	0	0	21.2
Wind: prevailing	NW	NW	SE	NW	NW	NW	NW	NE	SE	NW	NW	NW
Wind: secondary	NW	N	NW	NE	N	N	N	N	E	N	N	NW

\* Total rainfall (mm) 111; R H: relative humidity.

it drops to about 23°C. Their corresponding comfort zones are 26.5–30.5 and 21–25°C respectively. According to those limits the period from May to September requires either mechanical air conditioning or other passive cooling strategy.

- (2) According to the Olgyay method, Fig. 9, ventilation is the most effective strategy that can be used (42%), whereas radiation for heating utilizes about 17 and 21% of the time the condition falls within the comfort zone and requires no strategy. Active air conditioning and/or dehumidification utilizes about 21% of the time.
- (3) Givoni's method indicates that high mass building coupled with night time ventilation can effectively restore comfort (50%), Fig. 10. Furthermore, dehumidification and passive heating utilizes 13 and 17% of the time respectively, whereas only 17% of the time falls within the comfort zone.
- (4) Szokolay's method indicates strategies which are similar to those obtained using Givoni's method.
- (5) Mahony Tables indicate that high mass walls and light insulated roof should be used. The high mass building and outdoor sleeping is an effective strategy (43%).



Table 9  
Diagnosis

	J	F	M	A	M	J	J	A	S	O	N	D
Humidity group	3	3	3	3	2	2	3	3	3	3	3	3
Temperature (0°C)												
Monthly mean max.	21	22.1	26.3	31.3	38.6	39.7	41.3	40.6	38.3	33.6	29.8	20.4
Day comfort max.	29	29	29	29	31	31	29	29	29	29	29	29
Day comfort min.	23	23	23	23	25	25	23	23	23	23	23	23
Monthly mean min.	12.4	14.9	16.8	22	25.8	28	29.7	30	28.2	25	20.9	12.8
Night comfort max.	23	23	23	23	24	24	23	23	23	23	23	23
Night comfort min.	17	17	17	17	17	17	17	17	17	17	17	17
Thermal stress day	C	C	—	H	H	H	H	H	H	H	H	C
Thermal stress night	C	C	—	—	H	H	H	H	H	H	—	C

H: above comfort limit; —: within comfort limit; C: below comfort limit.

Table 10  
Indicators

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Humid				X						X	X		3
H1 Air movement													
H2 Air movement													
H3 Rain protection													
Arid													
A1 Thermal storage				X	X	X	X	X	—	—	—	—	5
A2 Outdoor sleeping					X	X	X	X	—	—	—	—	4
A3 Cold-season	X	X	—	—	—	—	—	—	—	—	—	X	3

Passive heating is required (25%) during the winter months and only 33% of the time falls within the comfort zone.

- (6) Table 12 compares the different approaches (Olgyay, Givoni, Szokolay and Mahony Tables) for building designs. It lists the appropriate strategy to restore comfort during the day and night independently. The bioclimatic charts and Mahony Tables indicate that in the early summer months (May and June), high mass building with night ventilation and outdoor night sleeping can restore comfort. Moreover, during the peak summer months (July–September) high mass building along with dehumidification and active air conditioning is required.

Table 11  
Design recommendations

Indicator total from Tabel (4)						Recommendations	
Humid			Arid				
H1	H2	H3	A1	A2	A3		
3	0	0	5	4	3		
						Layout	
						0–10 11 or 12	1. Building oriented on east to west axis to reduce exposure to sun
						5–12	x
						0–4	x
							2. Compact courtyard planning
						Spacing	
						11 or 12	3. Open spacing for breeze penetration.
						2–10	4. As 3, but protect from cold/hot wind
						0 or 1	x
							5. Compact planning.
						Air movement	
						3–12	x
							6. Rooms single banked. Permanent provision for air movement
						1 or 2	7. Double banked rooms with temporary provision for air movement.
						0–5	As 7
						6–12	As 7
						1 or 2	8. No air movement required
						0	2–12
						0	0 or 1
						Openings	
						0 or 1	9. Large openings, 40–80% of N and S walls
						11 or 12	10. Very small openings, 10–20%
						0 or 1	x
							11. Medium openings, 20–40%
						Walls	
						0–2	12. Light walls; short time lag
						3–12	x
							13. Heavy external and internal walls
						Roofs	
						0–5	x
						6–12	14. Light insulated roofs
							15. Heavy roofs; over 8 hours time lag
						Outdoor sleeping	
						2–12	x
							16. Space for outdoor sleeping required
						Rain protection	
						3–12	17. Protection from heavy rain needed

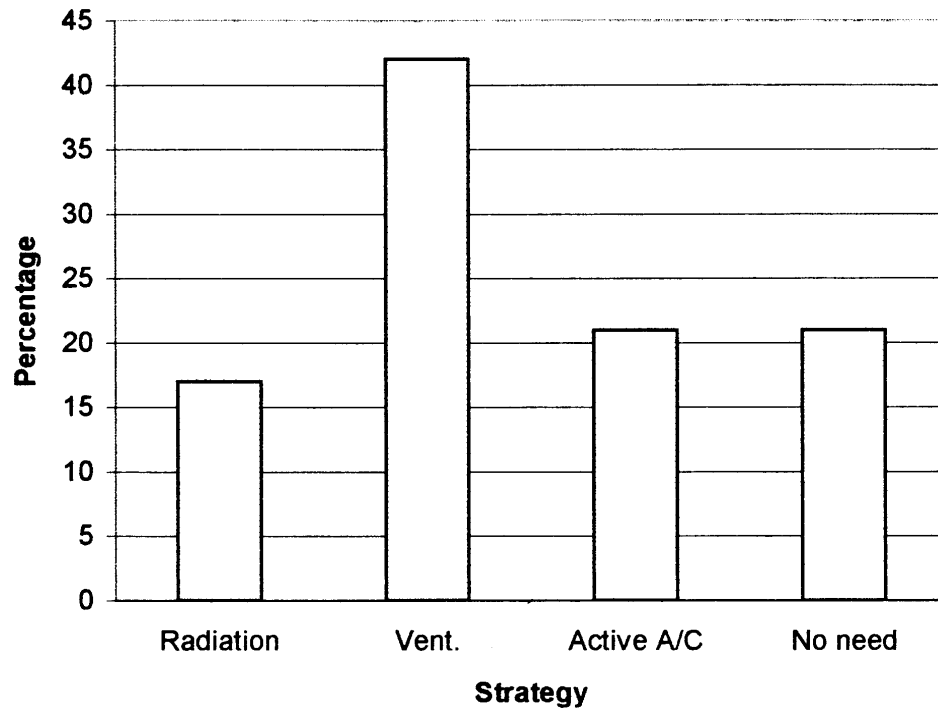


Fig. 9. Application of Olgyay method to Qatar.

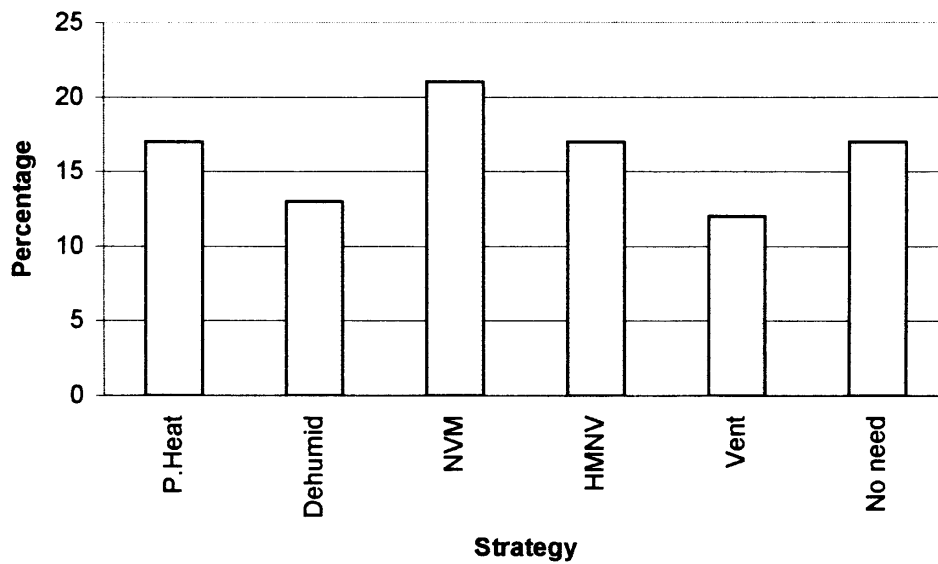


Fig. 10. Application of Givoni method to Qatar.

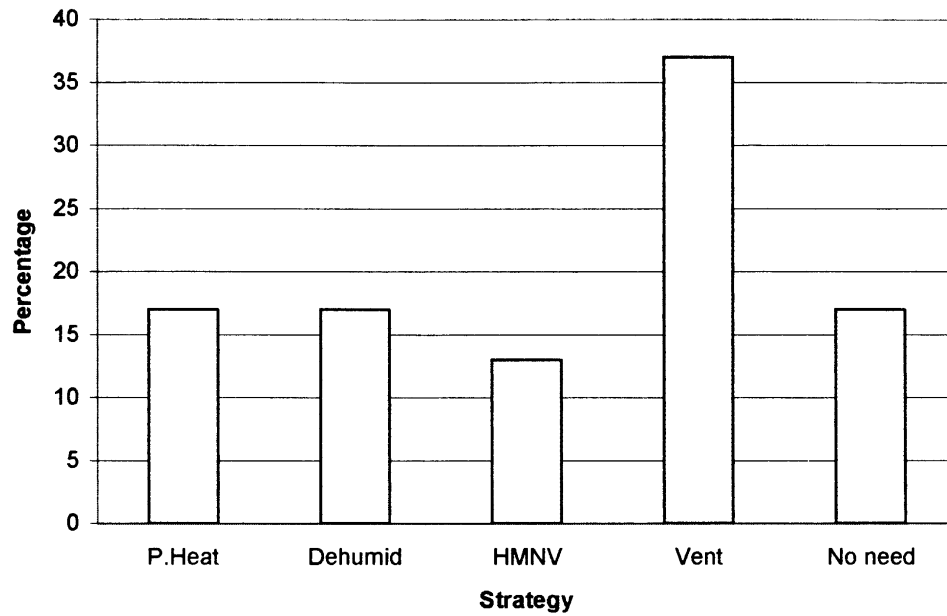


Fig. 11. Application of Szokolay method to Qatar.

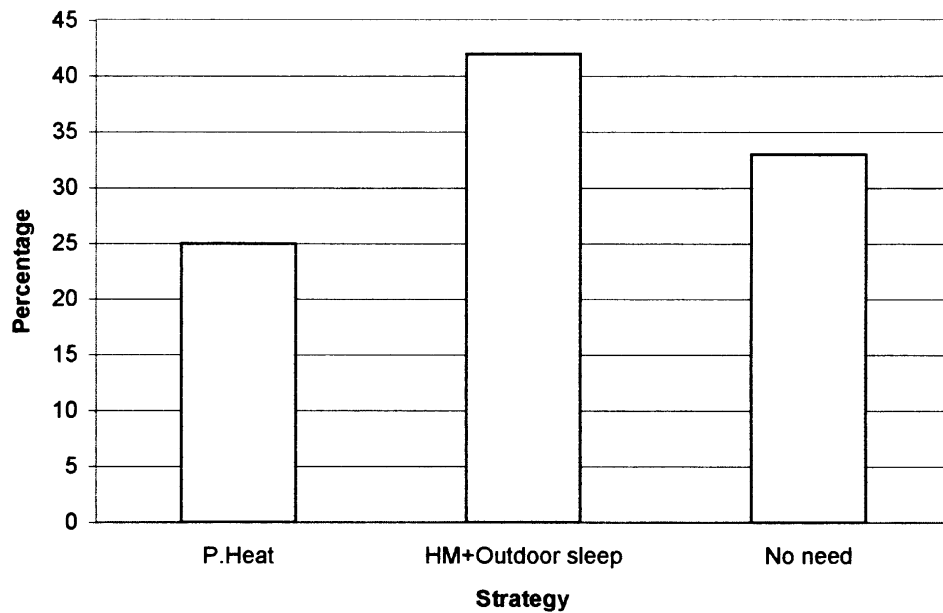


Fig. 12. Application of Mahony Tables to Qatar.

Table 12  
Comparison of different methods applied to Qatar

Month	Olgyays			Givoni		Szokolay		Mahony Tables	
Jan	Day	—	—	—	—	—	—	—	Passive heating
	Night	C	Radiation	C	Passive heating	C	Passive heating	C	
Feb	Day	—	—	—	—	—	—	—	Passive heating
	Night	C	Radiation	C	Passive heating	C	Passive heating	C	
Mar	Day	—	—	—	—	—	—	—	—
	Night	C	Radiation	C	Passive heating	C	Passive heating	C	
Apr	Day	H	Ventilation	H	HMNV + Ventilation	—	—	H	Thermal mass
	Night	—	—	—	—	—	—	—	
May	Day	H	Ventilation	H	HMNV	H	TMNV	H	Thermal mass + Outdoor night sleep
	Night	H	Ventilation	H	Ventilation	H	Ventilation	H	
Jun	Day	H	Ventilation	H	HMNV	H	TMNV	H	Thermal mass + Outdoor night sleep
	Night	H	Ventilation	H	Ventilation	H	Ventilation	H	
Jul	Day	H	Ventilation	H	HMNV	H	TMNV	H	Thermal mass + Outdoor night sleep
	Night	H	Active A/C	H	Dehumidification	H	Active A/C + Ventilation	H	
Aug	Day	H	Active A/C	H	Dehumidification	H	Dehumidification	H	Thermal mass + Outdoor night sleep
	Night	H	Active A/C	H	Dehumidification	H	Active A/C + Ventilation	H	
Sep	Day	H	Active A/C	H	HMV	H	TMNV + Dehumidification	H	—
	Night	H	Active A/C	H	NVM	H	Ventilation	H	
Oct	Day	H	Ventilation	H	NVM	H	Ventilation	H	—
	Night	H	Ventilation	H	NVM	H	Ventilation	H	
Nov	Day	H	Ventilation	H	NVM	H	Ventilation	H	—
	Night	H	Ventilation	H	NVM	H	Ventilation	H	
Dec	Day	—	—	—	—	C	Passive heating	—	Passive heating
	Night	C	Radiation	C	Passive heating	C	Passive heating	C	

H: above comfort limit; —: within comfort limit; C: below comfort limit.

## References

- [1] Anon: ASHRAE 55–74.
- [2] Macpherson RK, The assessment of the thermal environment—a review. *Br. J. Indust. Med.*, 1962;19.
- [3] Fanger, PO. Thermal comfort, analysis and applications in environmental engineering. Florida: Robert E. Kreiger Publishing Co., 1982.
- [4] Markus, TA, Morris EN. *Building, Climate and Energy*. Pitman Publishing Ltd, 1980.
- [5] Humphreys MA. Outdoor Temperature and comfort indoor. *Building Research and Practice* 1978;6(2):92–105.
- [6] Humphreys MA. Field studies of thermal comfort compared and applied. In: *Energy, heating and thermal comfort*. Lancaster (U.K.): BRE, The Construction Press, 1978a.
- [7] Olgyay V. *Design with climate, bioclimatic approach and architectural regionalism*. Princeton (NJ): Princeton University Press, 1963.
- [8] Givoni B. *Man, climate and architecture*. 2nd ed. London: Applied Science Publishers Ltd., 1967.
- [9] Watson D. Analysis of weather data for determining appropriate climate control strategies in architectural design. In: *Proceedings of the International Passive and Hybrid Cooling Conference*, Miami Beach. Haisley R, editor, Florida (U.S.A.): Solar Energy Association, 1981.
- [10] Szokolay SV. Climate analysis based on psychrometric chart. *Ambient Energy* 1986;7(4):171–81.
- [11] Arens EA, Blyholder AG, Schiller GE. Predicting thermal comfort of people in naturally ventilated buildings. *Symposium on Geothermal District Heating Modelling and Ground Water Heat Pump Applications*. AT-84-05, No. 4, 1984.
- [12] Givoni B. Comfort, climate analysis and building design guidelines. *Energy and Buildings* 1992;18:11–13.